# Missing Baryons at Low Redshift and Future Missions

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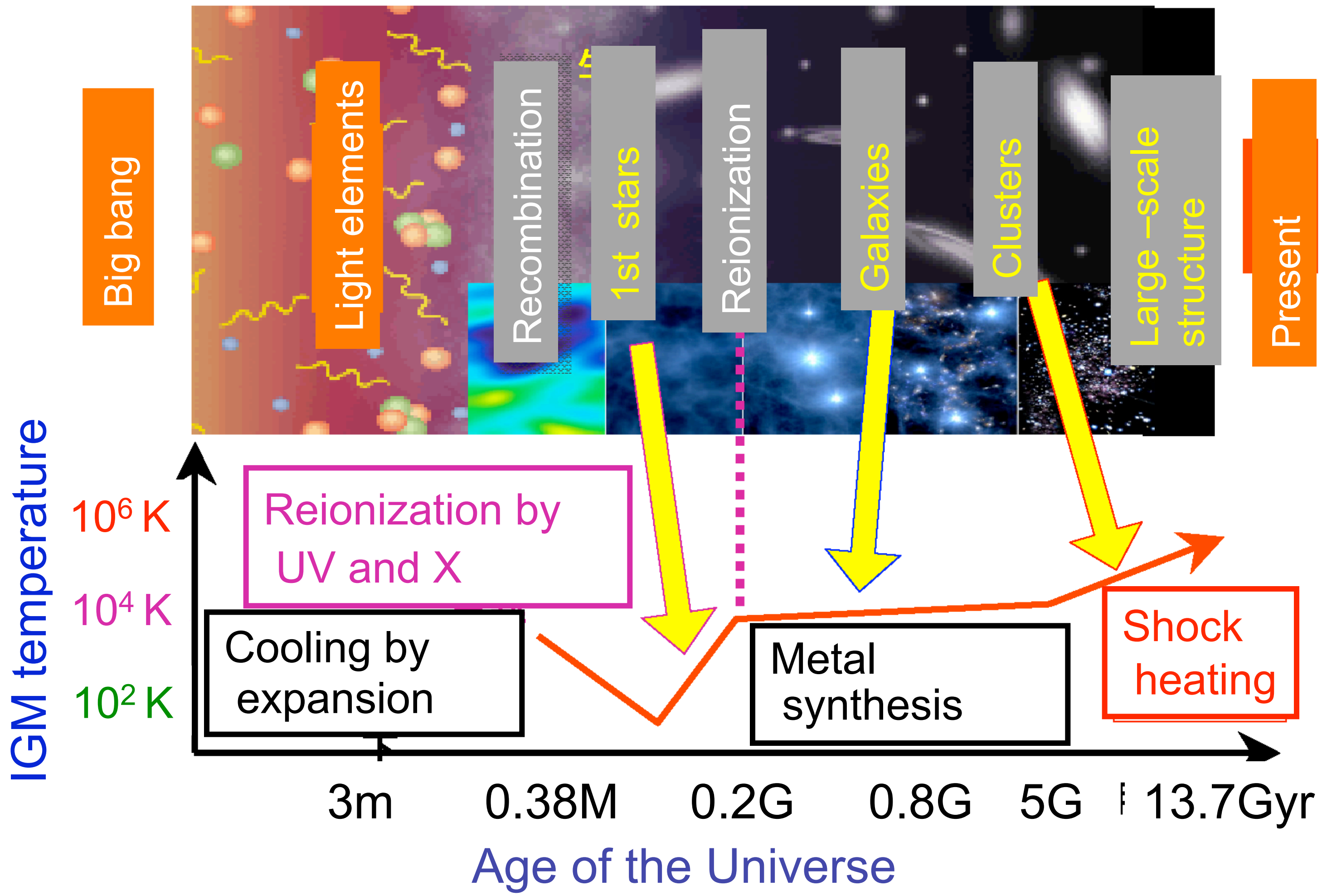
1. Science of WHIM
2. Suzaku search for WHIM
3. Future prospects

With Y. Takei, K. Sato, T. Tamura, A. Hoshino, T. Takahashi and others

# Thermal history of the universe




WHIM (warm-hot intergalactic medium) will tell us the evolution of the hot-phase material in the universe

# Cosmic structure

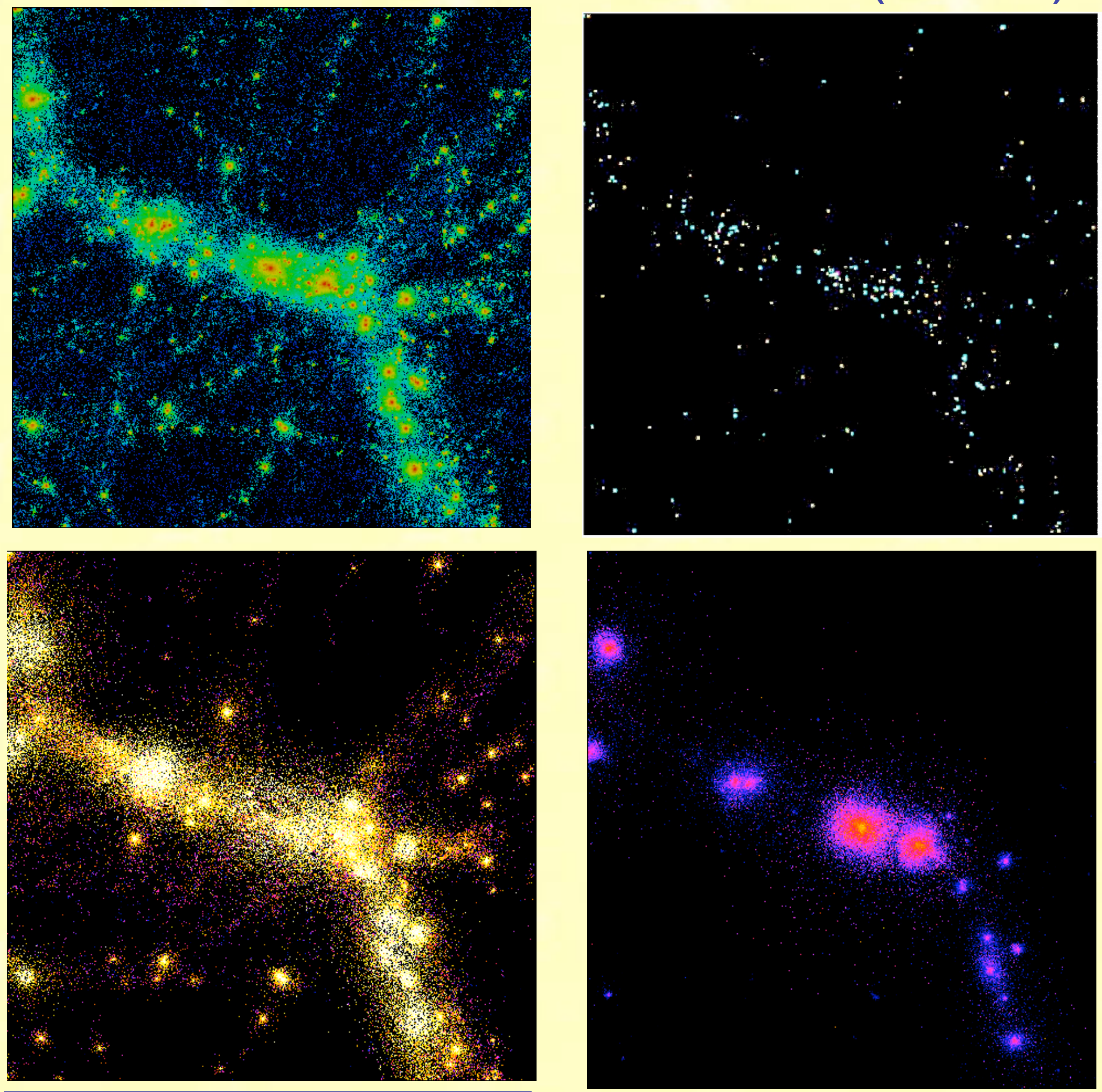
<u>WHIM</u> ($10^5$-$10^7$ K) traces the cosmic large-scale structure = "Missing baryon"

Typical matter density:
$\delta$ (=$n/\langle n_B \rangle$) = 10 - 100

Yoshikawa et al. 2001, ApJ, 558, 520

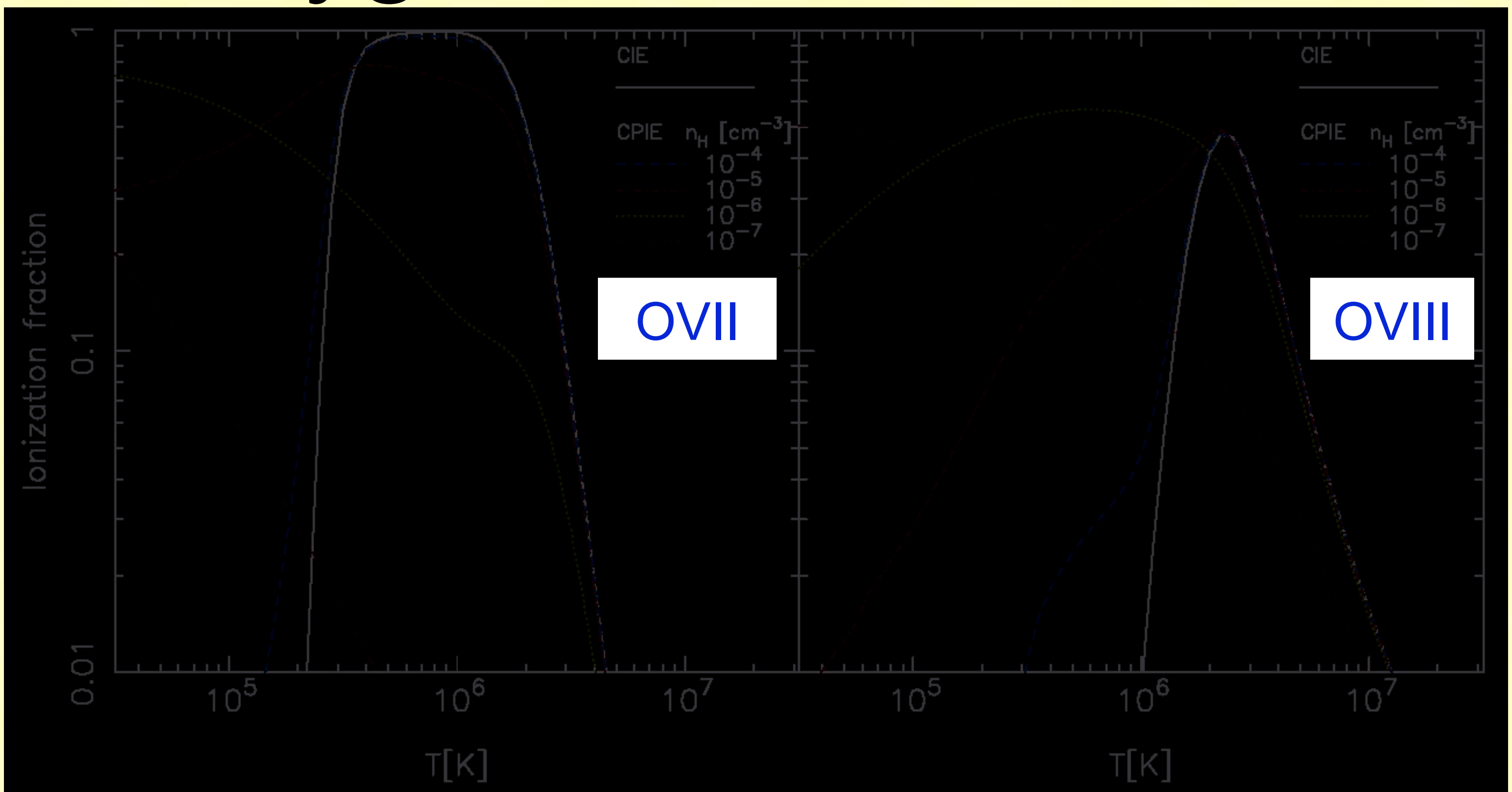
size = 30 $h^{-1}$ Mpc
$\approx$ 5 deg at $z$=0.1

Dark matter | Galaxies (~$10^4$K)



IGM ($10^5$-$10^7$K) | Cluster gas ($10^7$K)

# Oxygen emission line

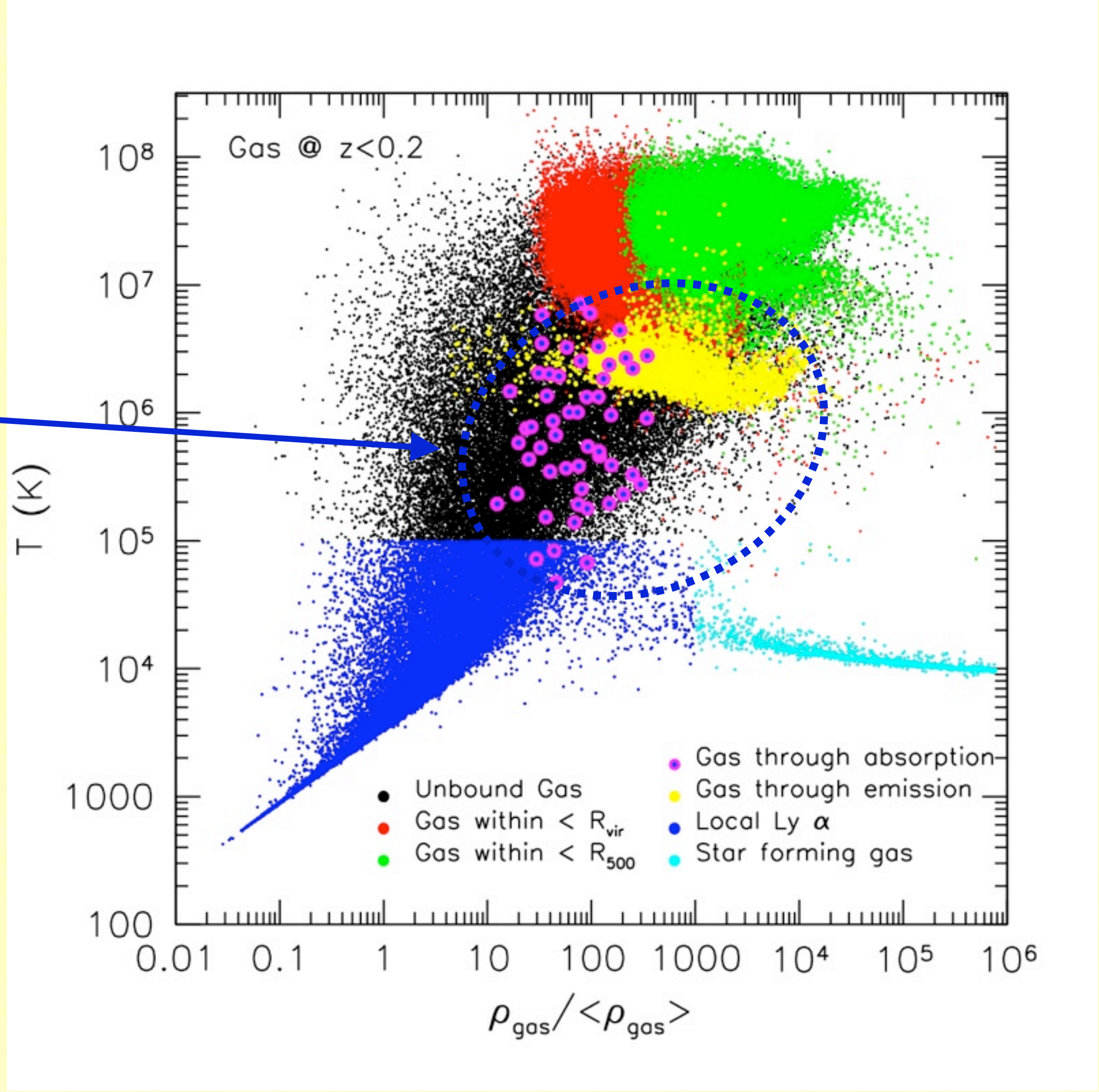



Kawahara et al. 06

- The best tool to explore dark baryon or WHIM in emission.
- Good energy resolution is essential to separate the ~100 times stronger Galactic/interplanetary emission

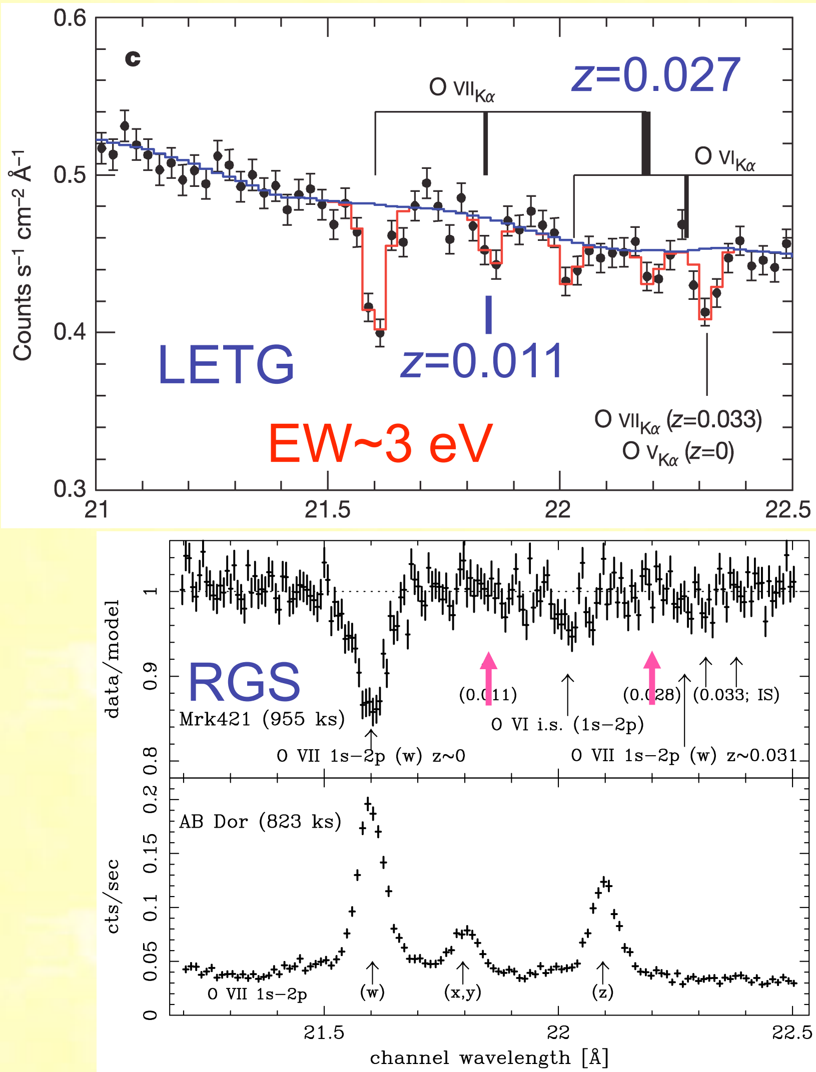
# Baryon phase

With X-ray absorption and emission lines, a wide area in the baryon phase space can be probed




EDGE consortium

# Absorption in Mrk421 spectrum



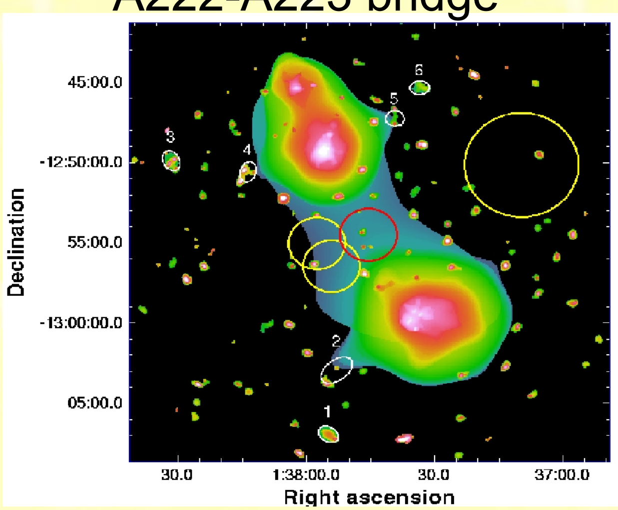

Nicastro et al. 05,Nature & ApJ
Kaastra et al. 06, ApJ
Rasmussen et al. 06, ApJ
Nicastro et al. 07, submitted

- LETG: OVII ($z$=0.011) detection significance = 3.9$\sigma$ ($P$*52bin=$10^{-6}$)
- Not significant if behavior of $\Sigma(\Delta\chi^2)$ for 7 lines with redshift trials is considered
- No absorption sign in RGS data
- LETG feature might be transient? (outflow from Mrk421?)
- Much more convincing evidence needed: with EDGE and XEUS

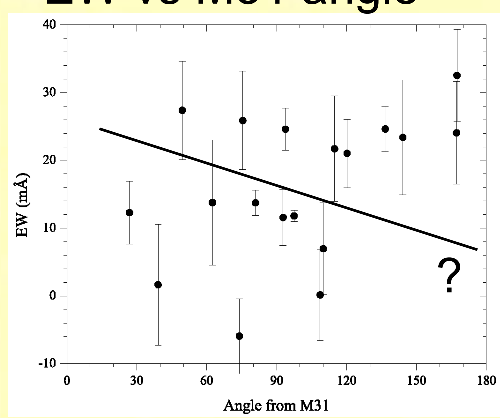
# Recent XMM results

- Werner et al. 2008: X-ray bridge between A222 and A223 ($z$ = 0.21)
  - kT ~ 0.9 keV, $\delta$ ~ 150, continuum only
- Bregman & Lloyd-Davis 2008: Local OVII absorption is due to Galactic halo (not by Local group medium)

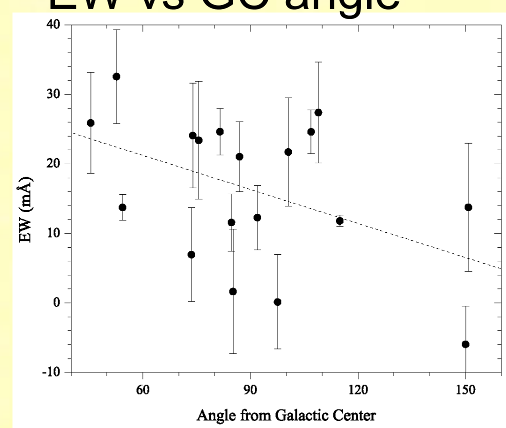
A222-A223 bridge



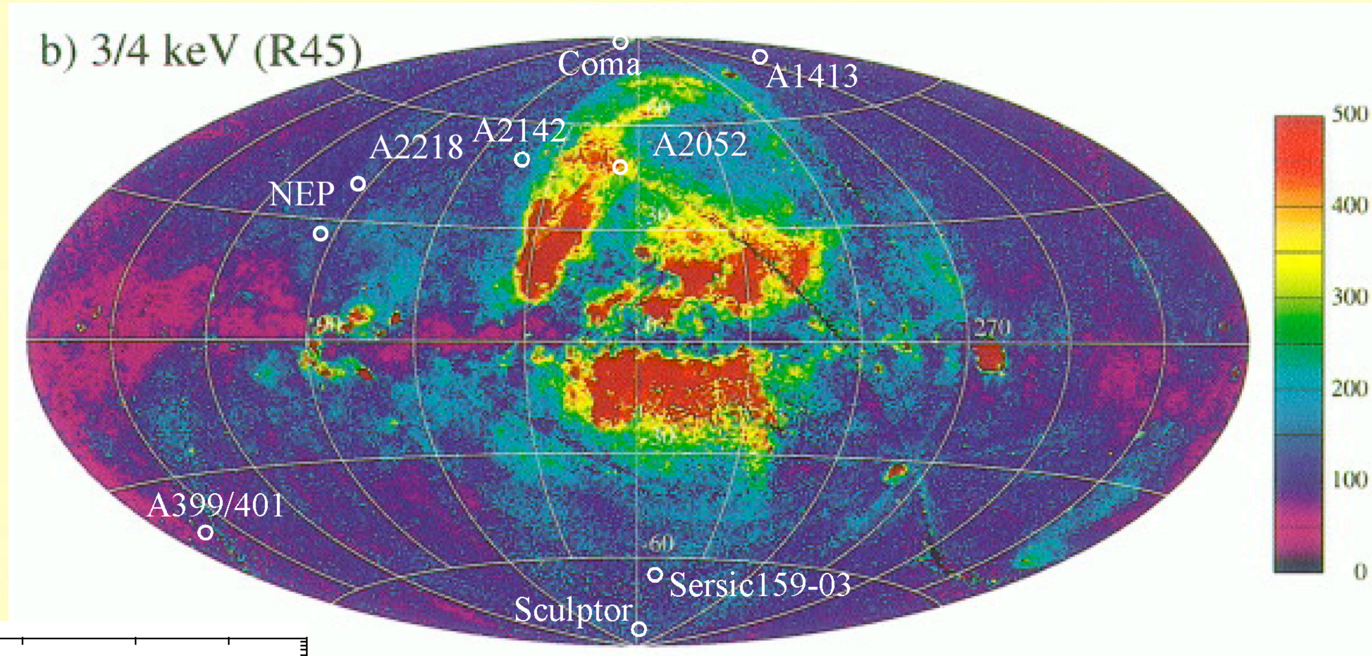

EW vs M31 angle



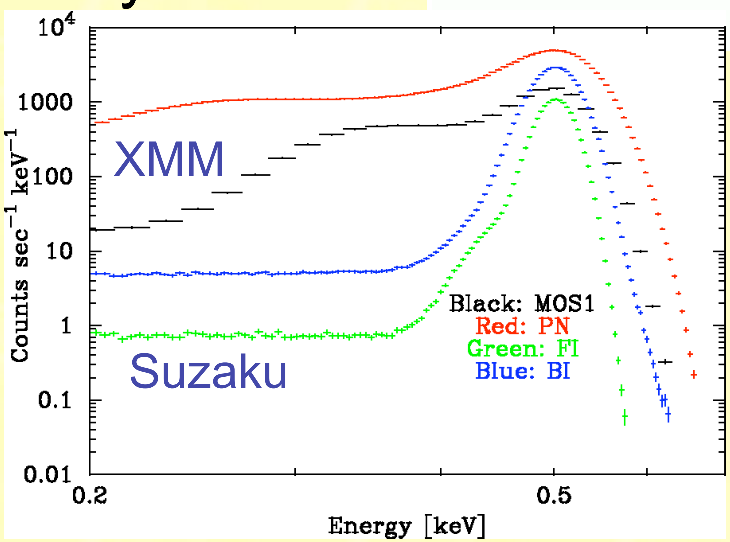

EW vs GC angle



# Suzaku study of cluster outskirts



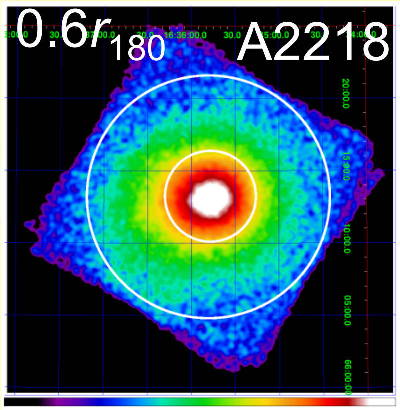

Why Suzaku?

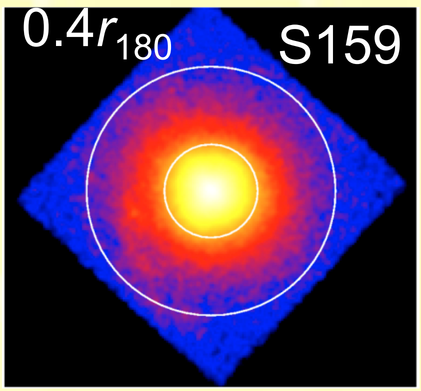


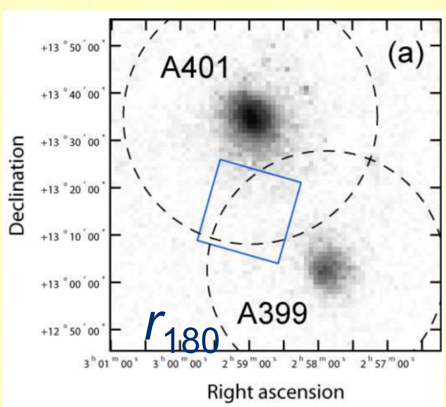

Snowden et al. 1995,1997

Good resolving power for oxygen lines

# A2218, Sérsic159 and A399/401



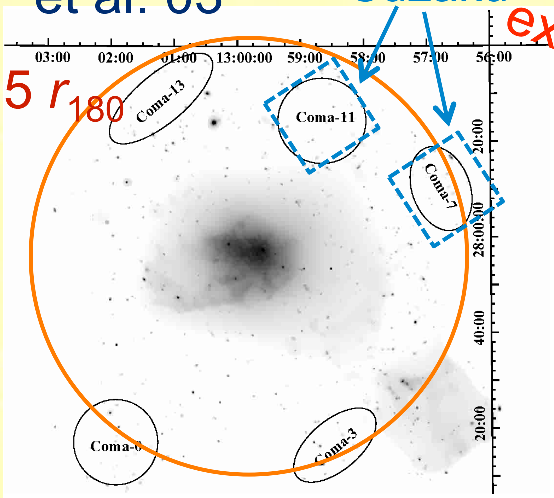

- A2218 (Takei et al. 07): $z$ = 0.1756
  - OVII line < 1 x $10^{-7}$ $cm^{-2}s^{-1}arcmin^{-2}$
  - $\delta$ < 270 ($0.1Z_{\odot}$, $L$ = 2 Mpc, 2 x$10^{6}$K)
- Sérsic 159-03 (Werner et al. 07, A10): $z$ = 0.0564
  - Non-thermal excess over the cluster
  - OVII line < 1.7 x $10^{-7}$ $cm^{-2}s^{-1}arcmin^{-2}$
  - $\delta$ < 410
- A399/A401 (Fujita et al. 07 PASJ Suzaku #2): Binary cluster at $z$=0.072 before merging
  - OVII line < 1 x $10^{-7}$ $cm^{-2}s^{-1}arcmin^{-2}$
  - $\delta$ < 310

# Coma outskirts

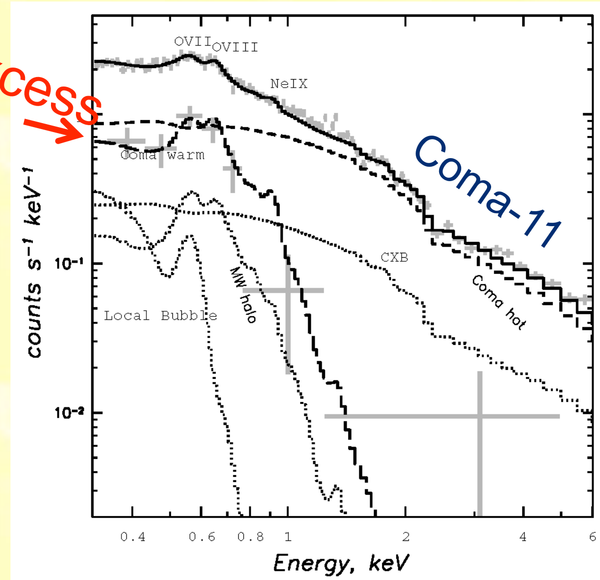
XMM: Finoguenov et al. 03

Suzaku

0.5 $r_{180}$

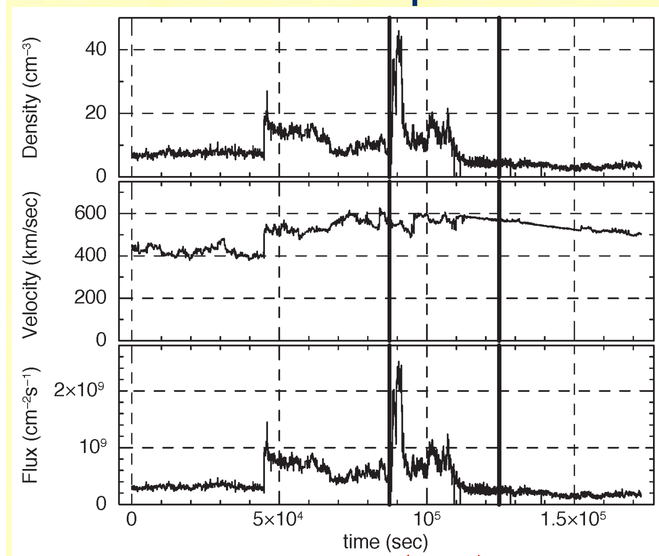



excess




Coma-11

Solar wind protons

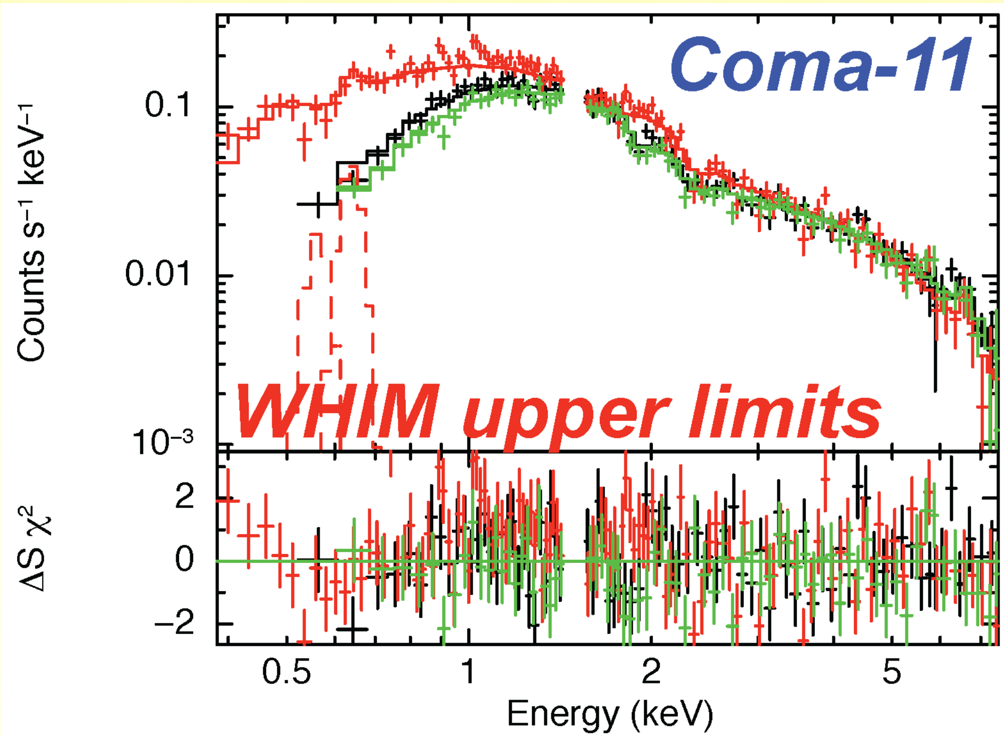


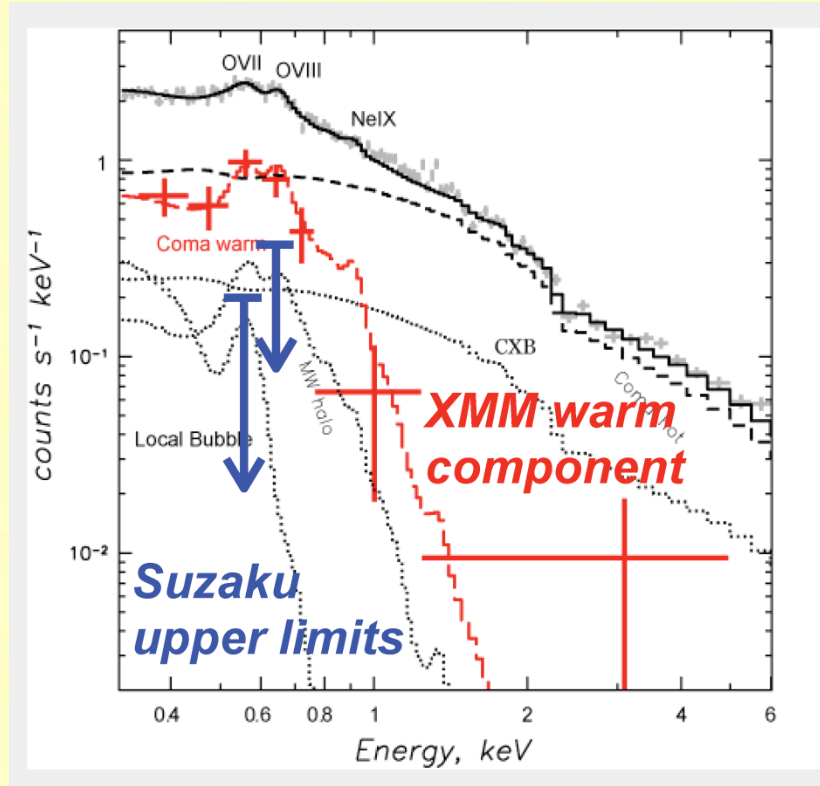

Coma with XMM

- XMM observation of Coma-11 field showed strong excess with OVII and OVIII lines, which are a few times stronger than the Galactic emission
- But, solar wind proton flux showed a flare-like feature during the XMM observation, which might have caused charge-exchange emission.

Takei et al. 2008

# Coma-11 Suzaku result

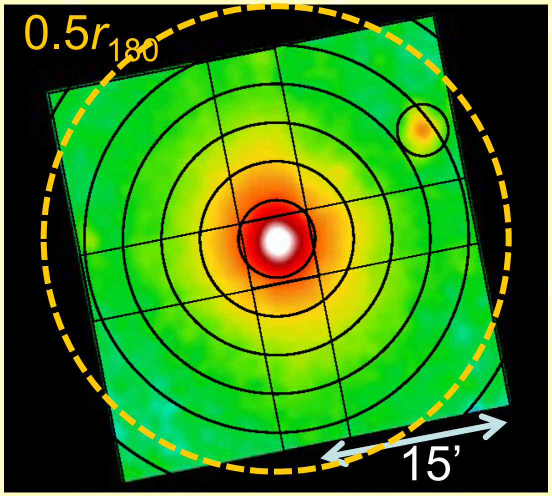


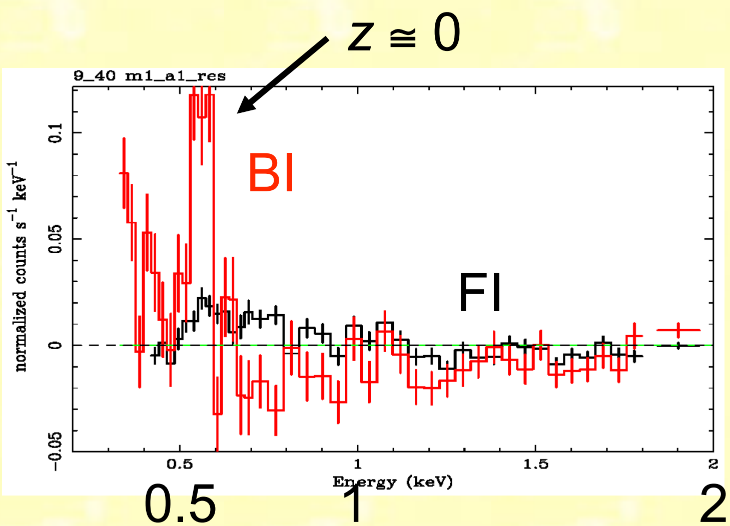

- Suzaku data show no significant OVII or OVIII feature, with OVII upper limit 2.3 times lower than the XMM flux ( $< 2.4 \times 10^{-7}$ $cm^{-2}$ $s^{-1}$ $arcmin^{-2}$).
- Overdensity: $\delta < 900\ (L/2\mathrm{Mpc})^{-1/2}\ (Z/0.1Z_{\odot}\mathrm{solar})^{-1/2}$

Tamura et al. 2008

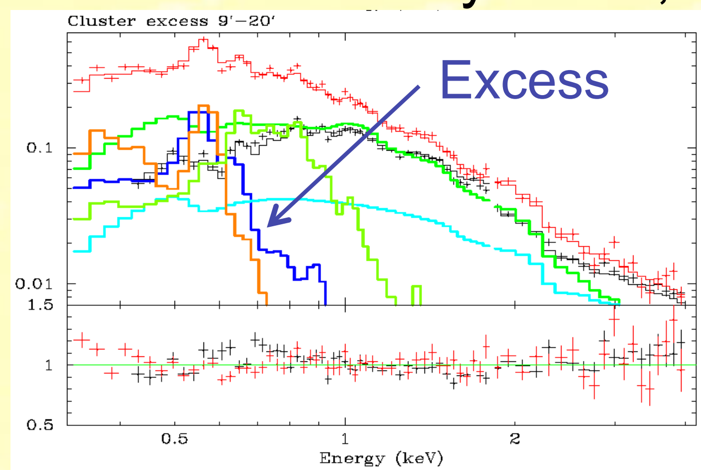
# A2052




- A nearby cluster: $z$ = 0.0355 and $kT$ = 3 keV
- Soft excess observed with XMM (Kaastra et al. 03)
- Suzaku observation: August 19-21, 2005 (very low contamination on XIS filter)
- 4 deg offset observation: July 14-15, 2007




Residual over ICM (1.5 keV), CXB and nominal Galactic emission

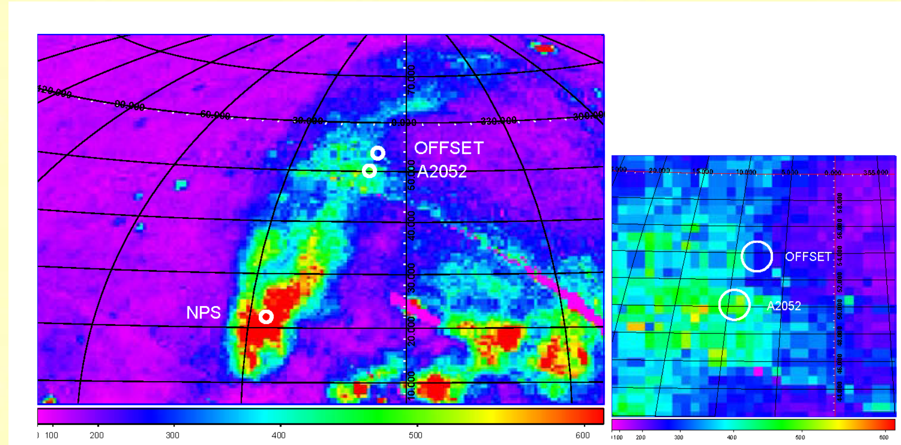



Residual spectrum can be fit with either brighter Galactic foreground or redshifted emission with $kT$ ~ 0.2 keV

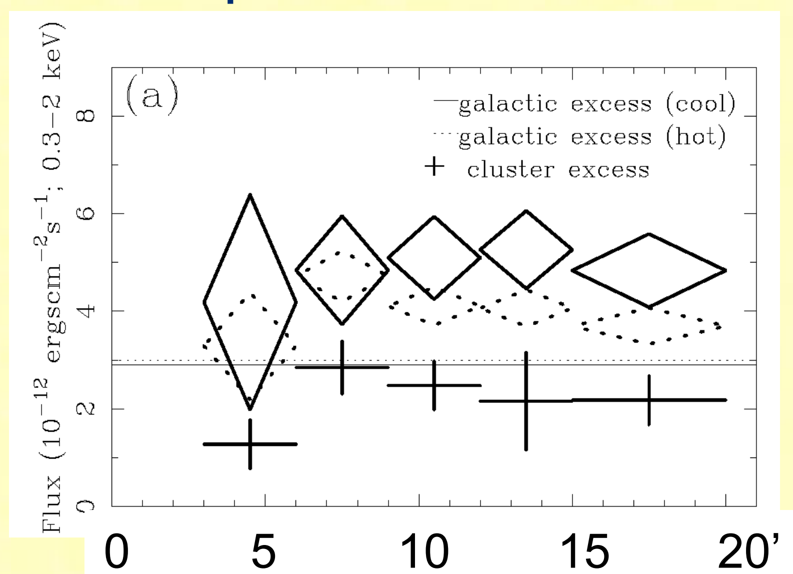
# More A2052

- Both A2052 and BGD regions are near the North Polar Spur, with enhanced soft X emission
- The excess component looks spatially uniform (Galactic?)
- If the 0.2 keV excess is due to WHIM-like gas at the cluster redshift
  $n_H \sim 1.7 \times 10^{-4}$ cm$^{-3}$ ($\delta \sim 900$) assuming $L$ = 2 Mpc, $Z$ = 0.1 solar

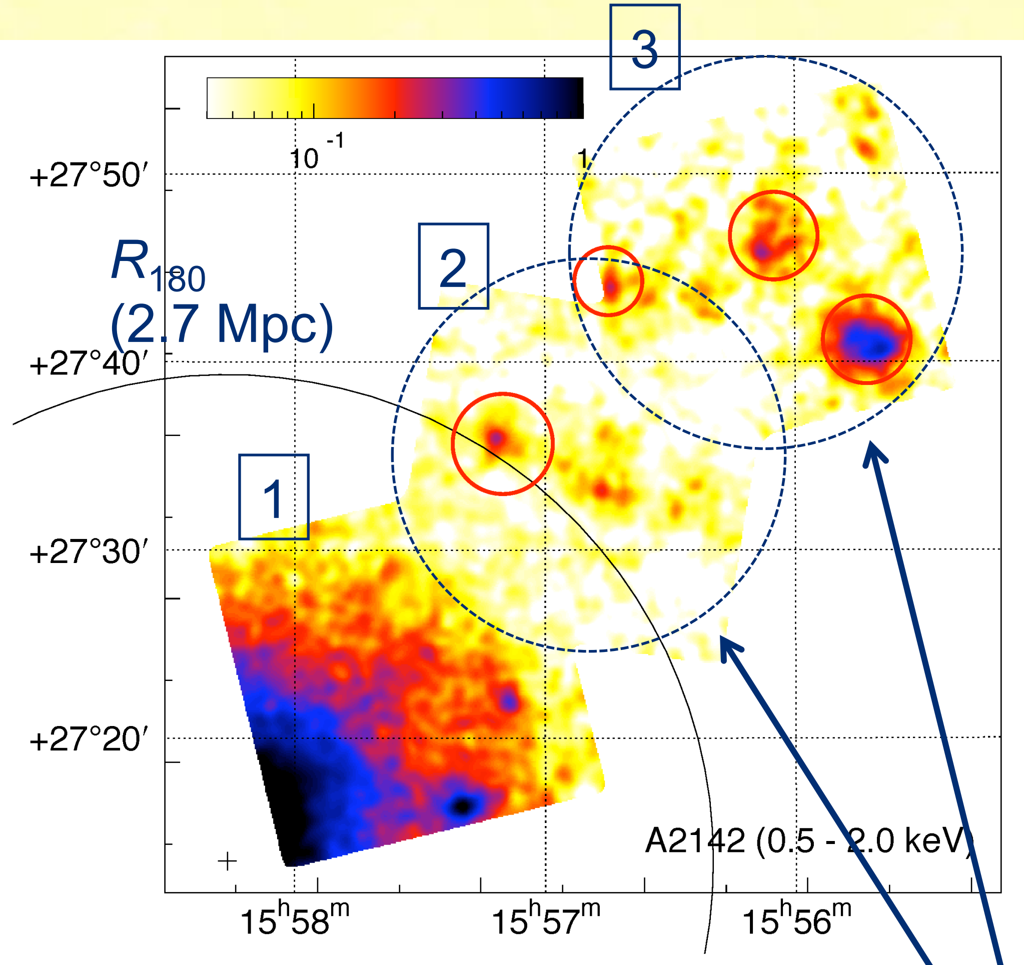
RASS ¾ keV map




Radial profile of the excess



# A2142 offset regions

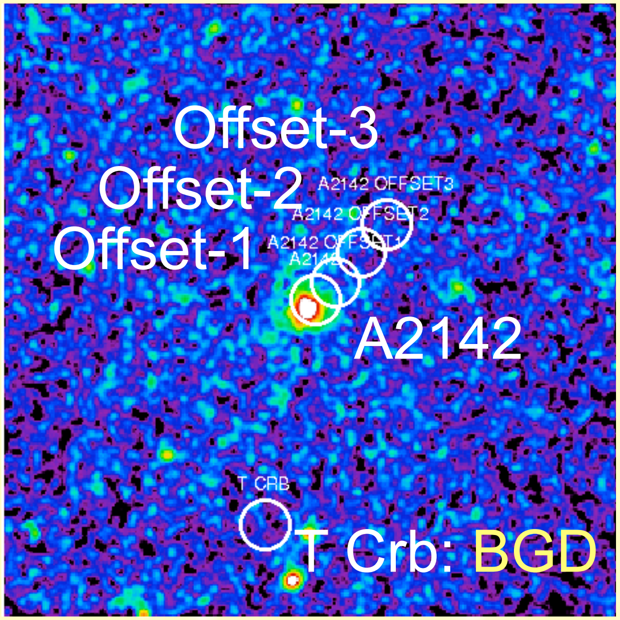


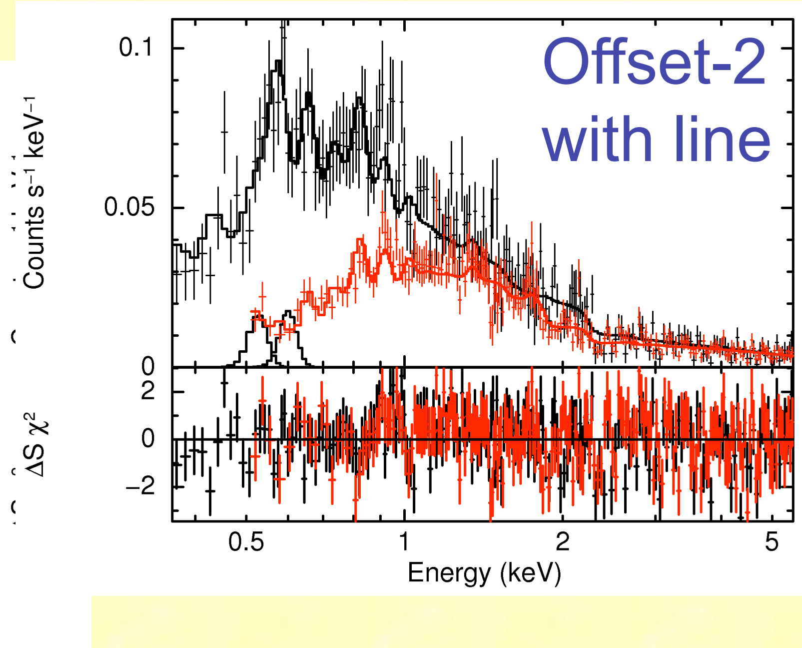

- The first cluster in which cold fronts were discovered by Markevitch et al. 2000.
- Offset regions along the merger axis were observed with Suzaku in August 2007
- $kT$ = 9 keV, $z$ = 0.0909 $r_{vir}$=2.66 Mpc =26.4'

Two offset regions show similar diffuse spectrum

# A2142 Suzaku results

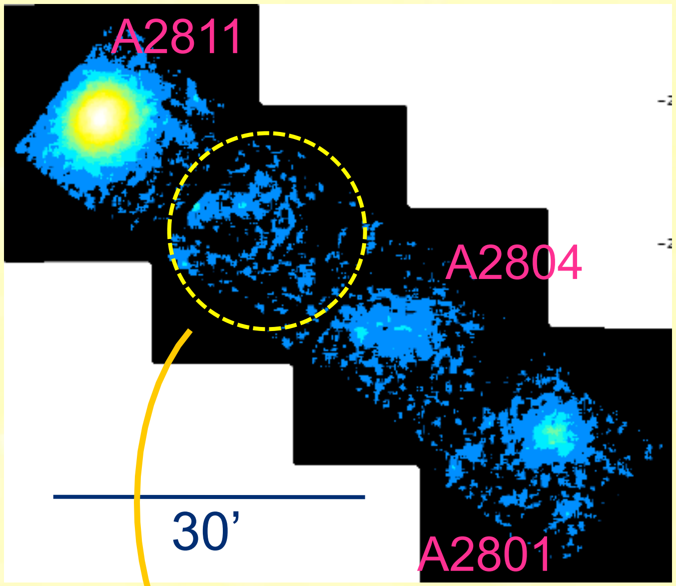
- BGD was taken at 1.4° offset region
- Offset-2 region (90% statitical error)
  - OVII: $7.1 \pm 3.7 \times 10^{-8}$ cm$^{-2}$s$^{-1}$amin$^{-2}$
  - OVIII: $9.2 \pm 5.3 \times 10^{-8}$ cm$^{-2}$s$^{-1}$amin$^{-2}$
- OVII flux implies $\delta = 250 \pm 130$
- However, systematic error (energy scale, resolution, contamination) is about $1 \times 10^{-7}$ cm$^{-2}$s$^{-1}$amin$^{-2}$, so it is still an upper limit ($< 1.2 \times 10^{-7}$ cm$^{-2}$s$^{-1}$amin$^{-2}$).

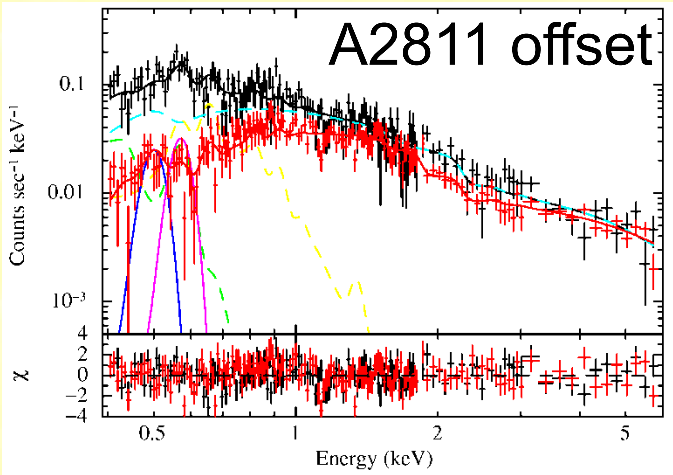


# Sculptor supercluster

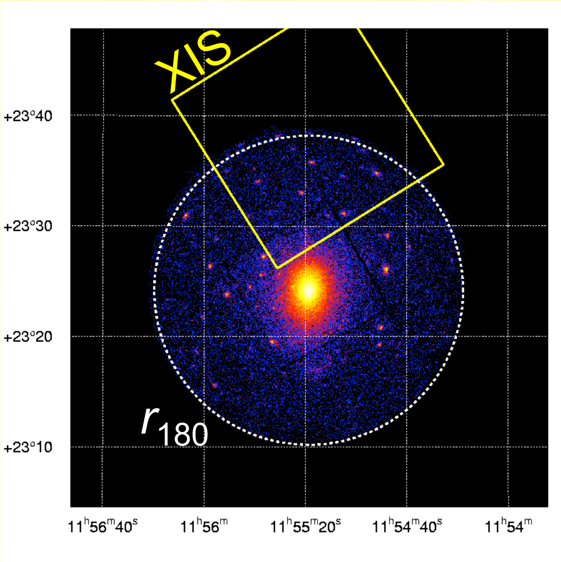
- 6 X-ray clusters at $z$ = 0.11, observed in Nov. 27-29, 2005
- XIS data suggested excess emission with $kT \sim 0.8$ keV (Kelley et al.: Suzaku 2006)
- A2811-offset region was further analyzed
- Upper limits ($2\sigma$) to O lines:
  OVII: 1.2–1.4 x $10^{-7}$ $cm^{-2}s^{-1}$ $arcmin^{-2}$
  $\rightarrow \delta < 350$ ($2 \times 10^6$K, 2Mpc, $0.1Z_{\odot}$)
  OVIII: 2–3 x $10^{-7}$ $cm^{-2}s^{-1}$ $arcmin^{-2}$

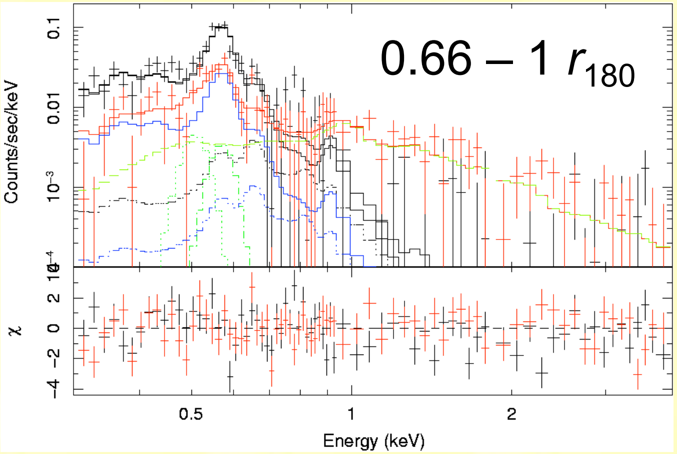


# A1413

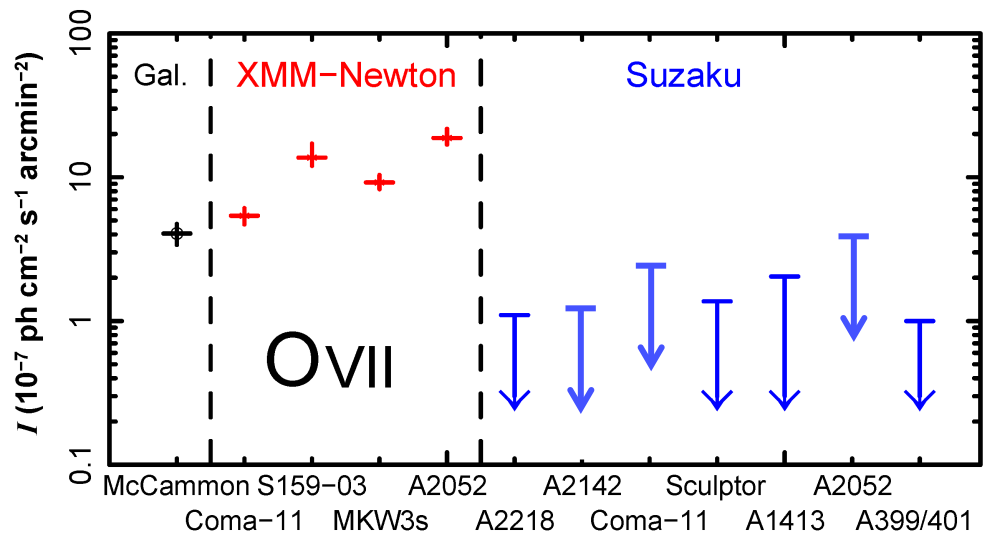
- A relaxed cluster at $z = 0.143$
- Suzaku offset pointing was done in Nov. 15-18, 2005
- $2\sigma$ upper limits to O lines in $0.66 - 1\ r_{180}$ (10'−15'):
  OVII: $2.0 \times 10^{-7}$ cm$^{-2}$s$^{-1}$arcmin$^{-2}$
  OVIII: $1.6 \times 10^{-7}$ cm$^{-2}$s$^{-1}$arcmin$^{-2}$
  with BGD in the same field
- With the same assumption of 0.1 solar, $2 \times 10^6$ K and $L = 2$ Mpc, $\delta < 400$
  is implied by the OVII upper limit

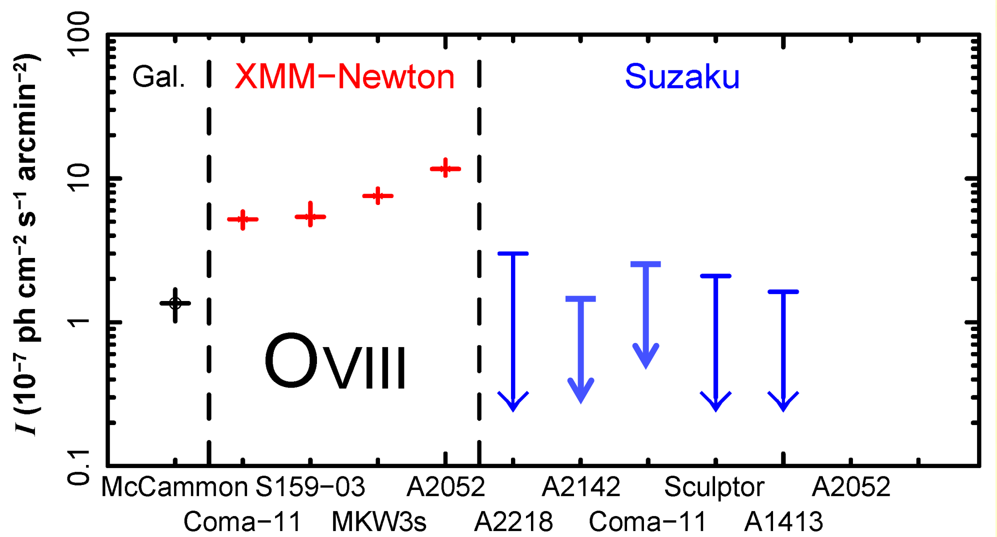



Hoshino et al. in prep.

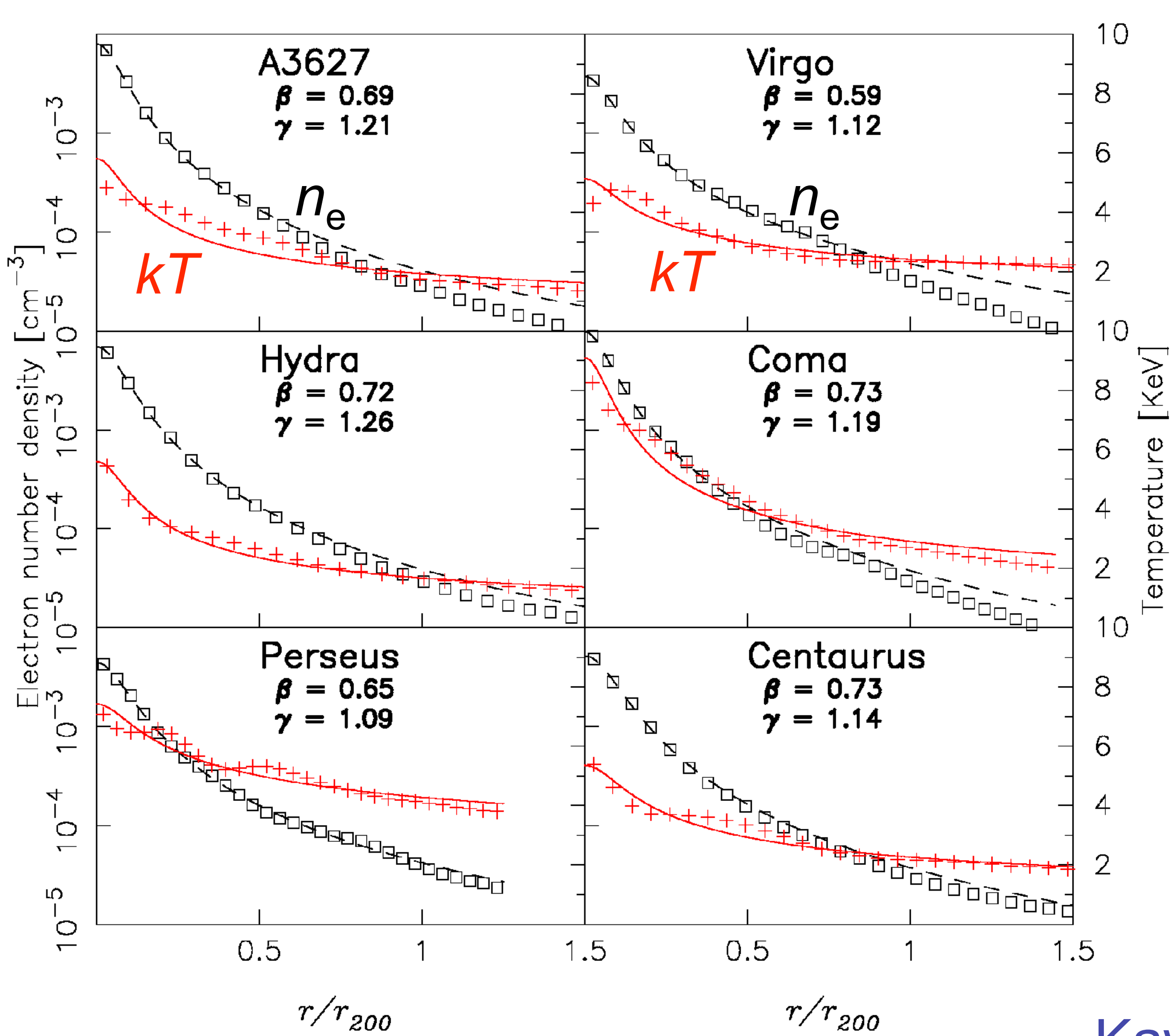
# Summary of Suzaku constraints




- Suzaku upper limits on Oxygen lines are factor of 3 -5 lower than the XMM "detection".
- Understanding the spectrum of Galactic emission is most important
- Detector background and solar wind process also cause significant effect on oxygen measurement
- Long on-off observation?

# Cluster outskirts: Simulation




At $r_{200}$:
- $kT \sim 2$ keV and
- $n_e \sim 3 \times 10^{-5}$ cm$^{-3}$
- ($\delta \sim 180$)

Quite hot even at $1.5\, r_{200}$ : may be too hot to look for oxygen lines

Then, how clusters are connected to WHIM filaments?

Mean hydrogen density

$$\langle n_H \rangle = 1.77 \times 10^{-7} (1+z)^3$$

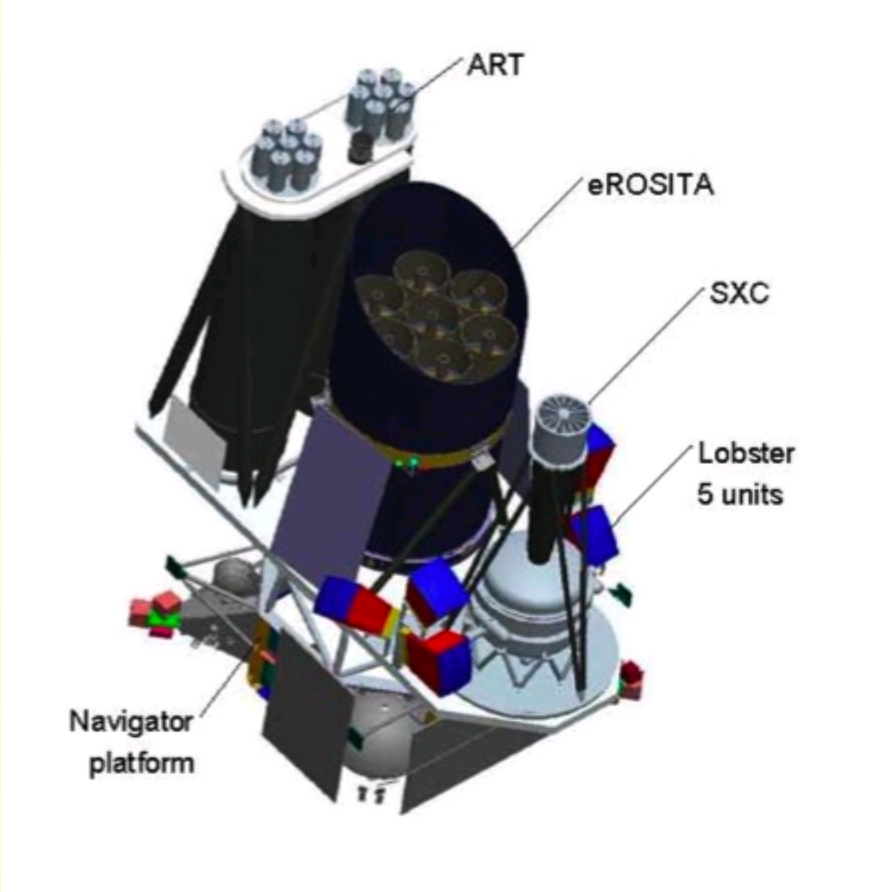
Kawahara priv. comm

# Summary of Suzaku study

- WHIM or missing baryons carry important science about structure formation and chemical /thermal evolution of the universe
- Its detection is a challenge for X-ray astronomy
- Suzaku is giving fairly low upper limits ($\delta < 300$) , but actual density around clusters is $\delta \sim 100$
- Suzaku may be able to find dense clamps of WHIM in cluster outskirts and in superclusters, which will be the first signature of WHIM

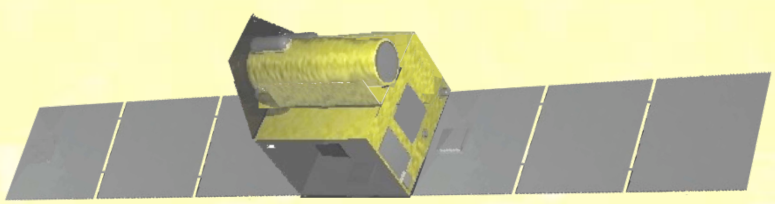
# Spectrum Röntgen Gamma

- Talks by
  G. Hasinger
  (eROSITA)
  and
  J-W den Herder
  (SXC)

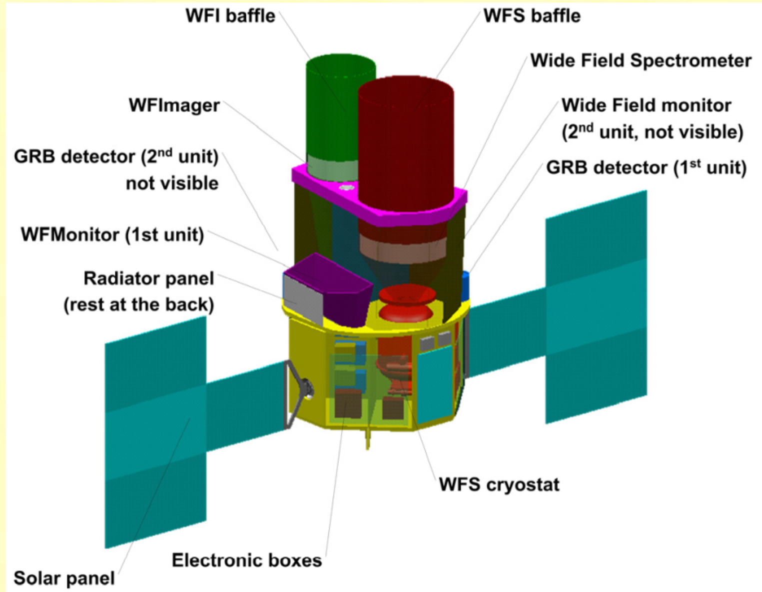


# XENIA/EDGE and DIOS

- TES calorimeter array with 1024 pixels
- DIOS (Diffuse Intergalactic Oxygen Surveyor, Japan) … small mission ~400 kg
- EDGE (Explorer of Diffuse emission and Gamma-ray burst Explosions) … medium size ~2000 kg
  ⇒ XENIA (Kouveliotou, Piro, den Herder) for US proposal
- Launch: 2015 or later
- Very wide field of view (~ 1deg) with 4-reflection X-ray telescope
- Energy range < 2 keV

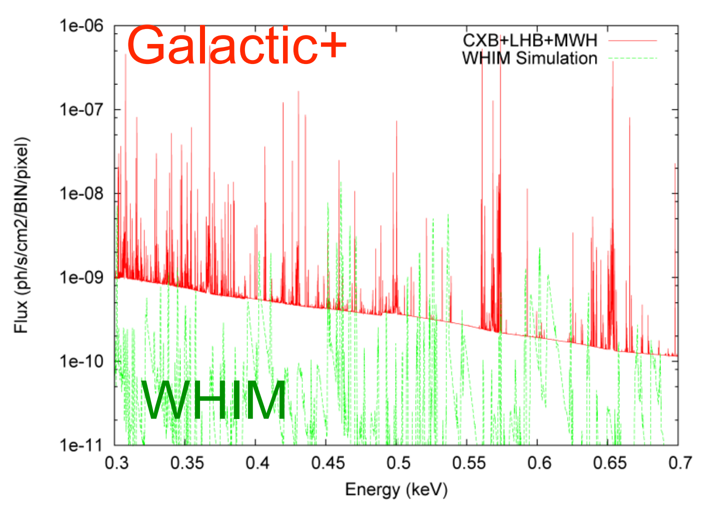


DIOS: Japanese small satellite

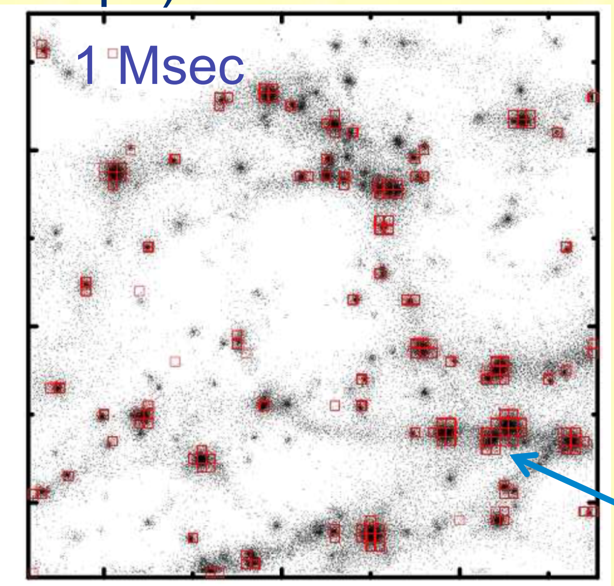



EDGE/XENIA: US-Europe-J

Incident spectrum



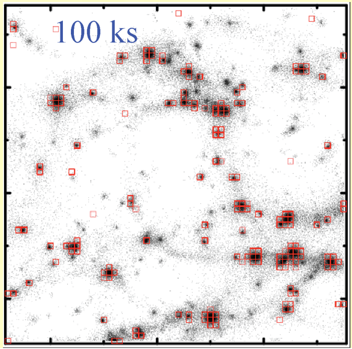

5 deg x 5 deg at $z$ = 0.2 (60 Mpc)




OVII & OVIII > 3$\sigma$

# Expected results

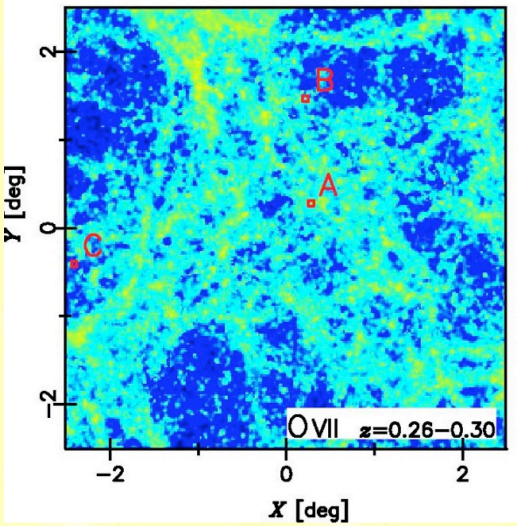
- 0.1-1 Msec exposure with EDGE/XENIA ($S\Omega$~ 1000 cm$^2$ deg$^2$) gives significant detection of WHIM filaments
- Combined detection of OVII and OVIII lines suppresses spurious features
- EDGE/XENIA has capability of absorption measurement against GRB afterglow → density and depth of the filament



# Expectation from XEUS

- Kawahara et al. 06 computed the mock transmission spectra of the WHIM based on hydrodynamic simulation data.
  - a light-cone output for $0 < z < 0.3$
  - mock spectra for a bright source
- Cosmological Hydrodynamic Simulation (Yoshikawa et al. 01)
  - PPPM/SPH ($128^3$ DM and gas particles, $L_{\mathrm{box}} = 75h^{-1}$ Mpc)
  - $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $\Omega_b = 0.015h^{-2,}$ $h = 0.7$, $\sigma_8 = 1.0$
  - note: $\Omega_b$ is ~30 % smaller than the recent estimate.

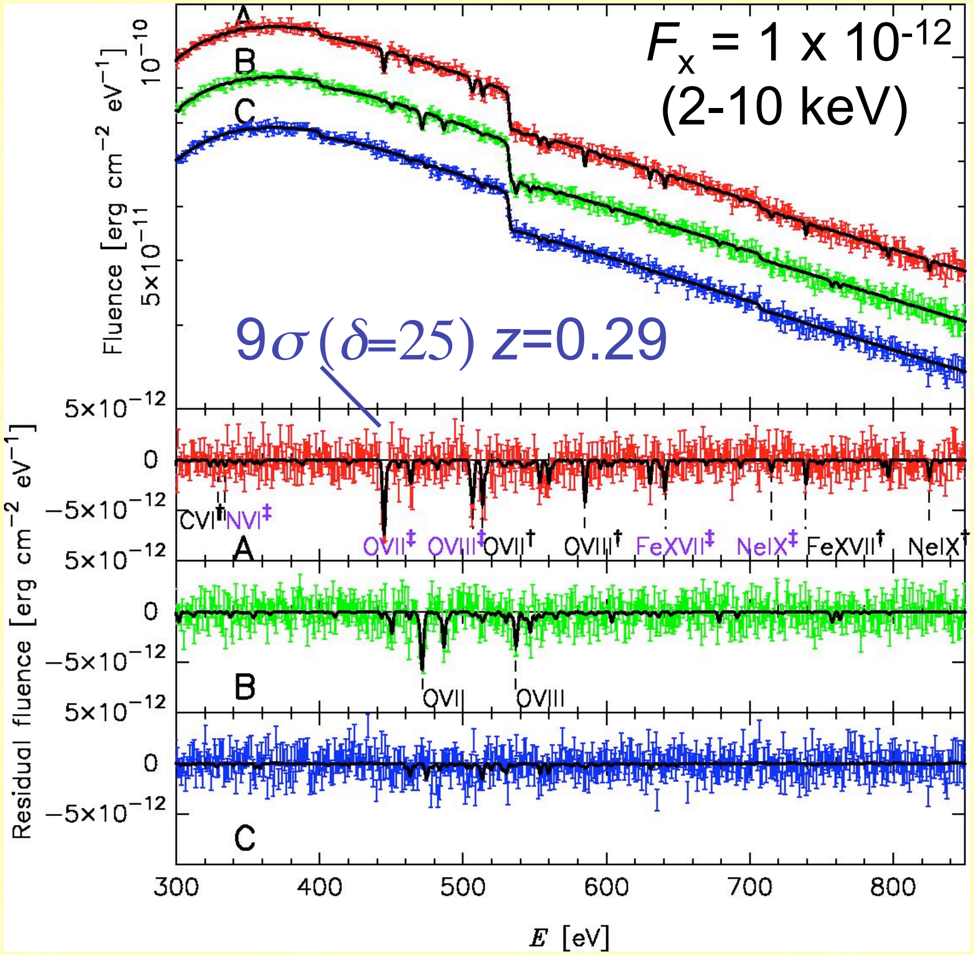
OVII: $z$=0.26-0.30, 5 deg = 76 Mpc




$N_{\mathrm{OVII}}=10^{15}$-$10^{16}$ cm$^{-2}$

But, 60000 cm$^2$ was assumed

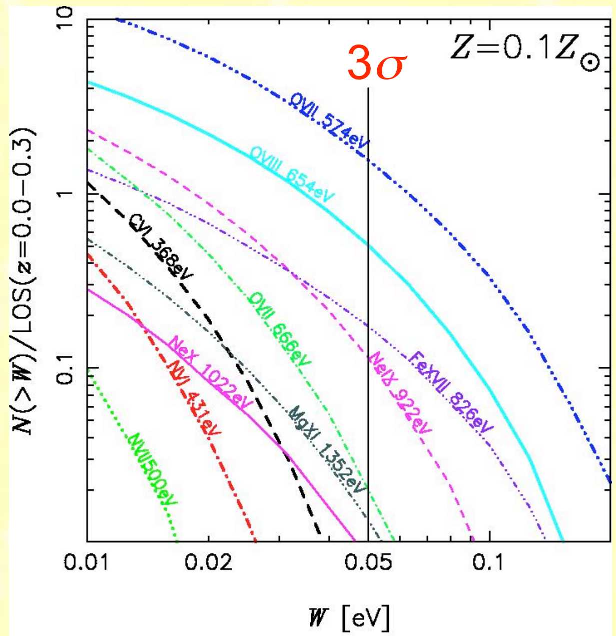
# Simulated spectra




Expected number of absorption system per LOS

| | $S/N \geq 3$ |
|---|---|
| OVII (574 eV) | 1.71 |
| OVIII (654 eV) | 0.43 |
| OVII and OVIII | 0.41 |

for 30 ksec obs.

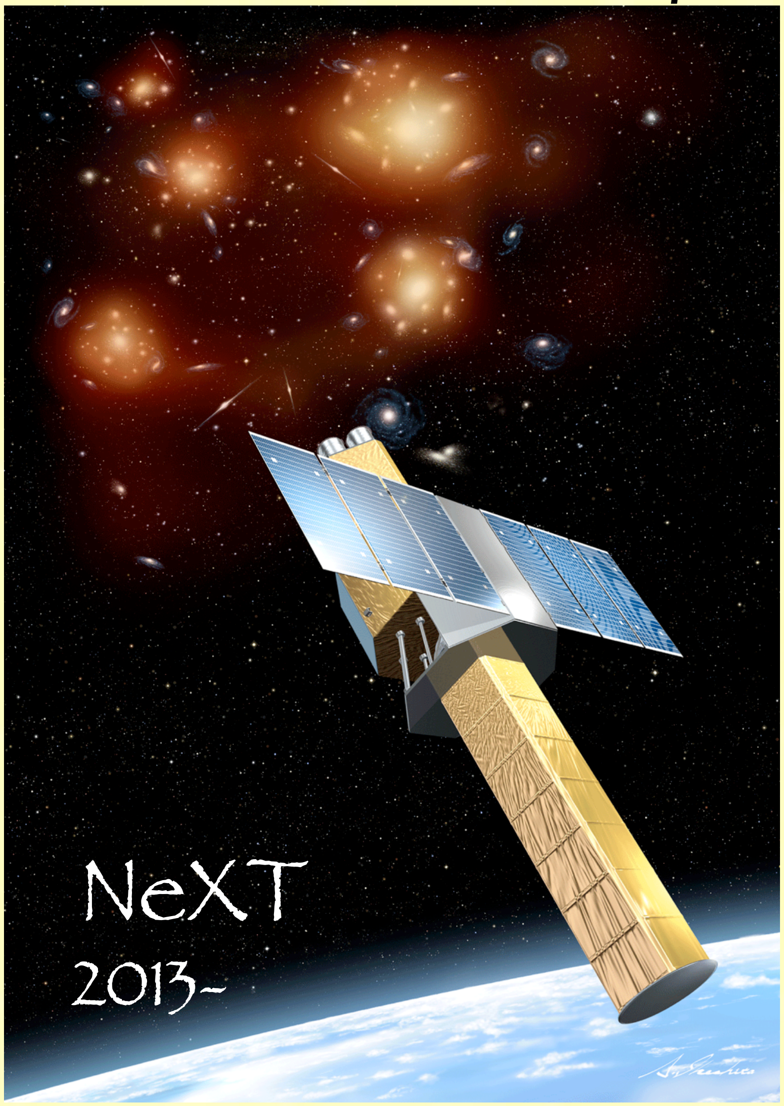



$$N_{\mathrm{OVII}} = 1.3\times10^{15}\,(EW\,/\,0.1\mathrm{eV})\,\mathrm{cm}^{-2}$$

EW=0.05 eV : 3$\sigma$ for 30 ksec with XEUS

# *NEXT*

*New Exploration X-ray Telescope*




Takahashi et al. 06, SPIE

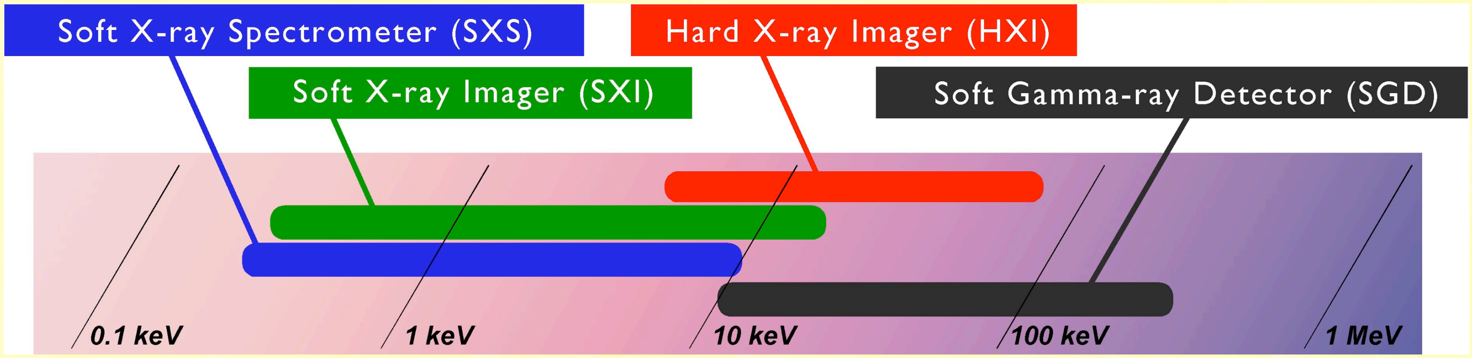
International X-ray Observatory in 2010's

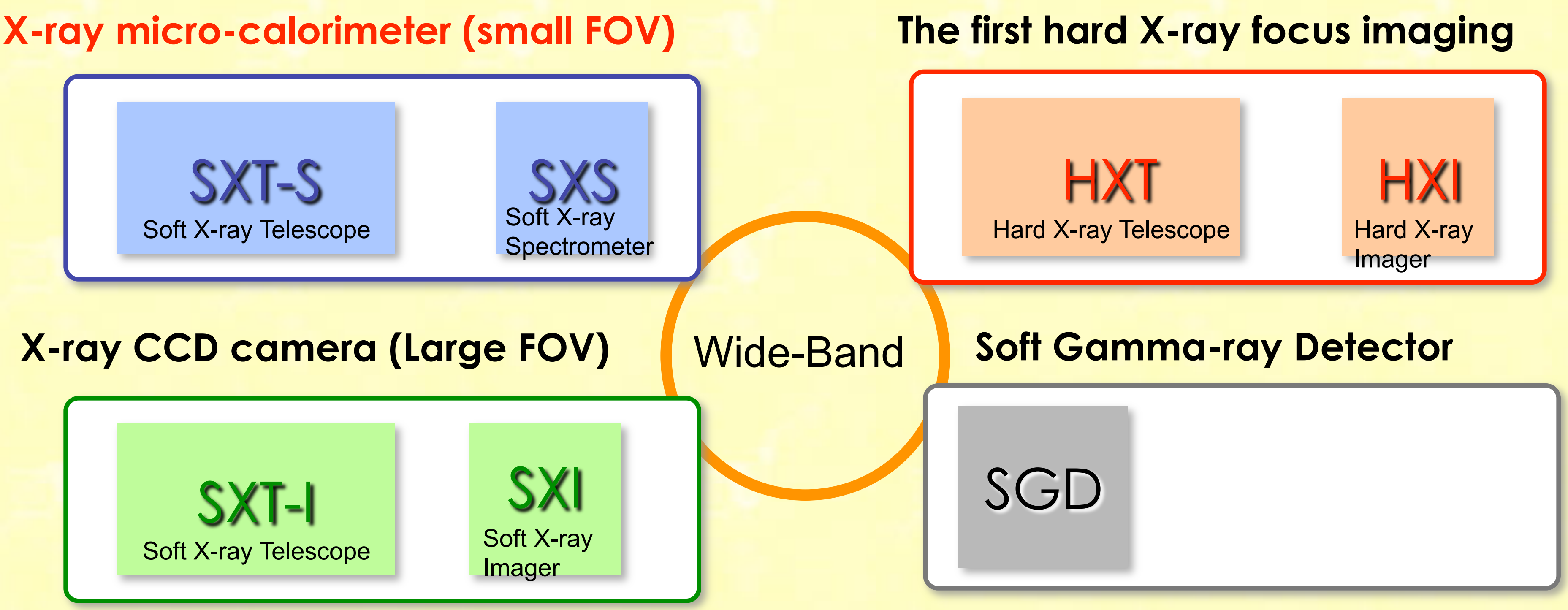
Phase A since 2007
Target Launch 2013
Launch Vehicle : H2A

- Phase A study has started.
- A review required to start Phase B will take place in May 2008.

NuStar (2011) / Simbol-X (2013)
(Hard X-ray Imaging Only)

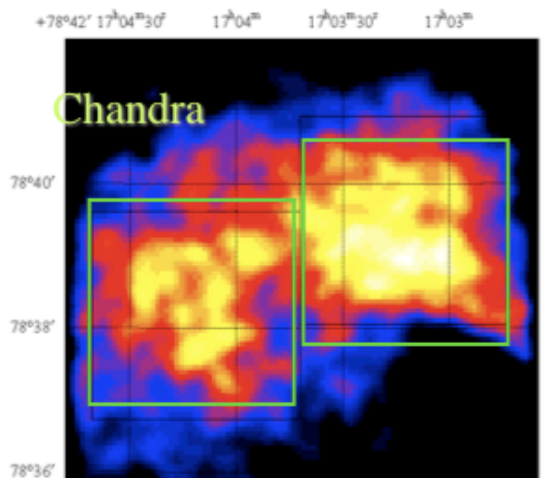
# NeXT Baseline Configuration



## New Science brought by the power of micro calorimeter

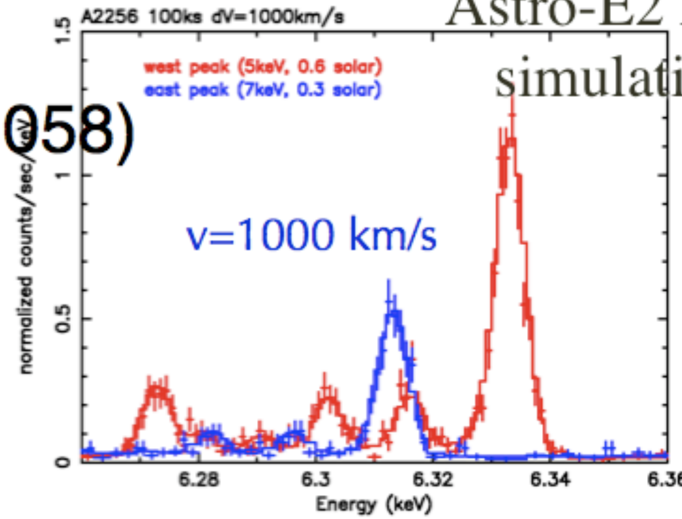
# Bulk motion, turbulence & ion temperature

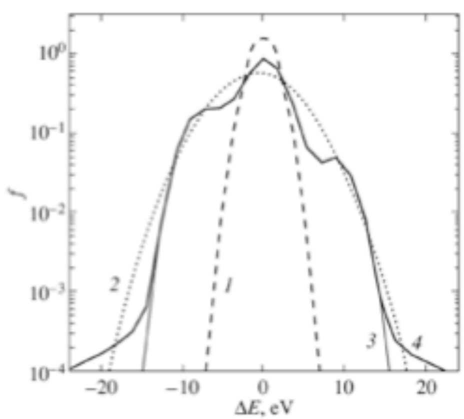



Sun et al. 2002

A2256 ($z = 0.058$)
(PV target)

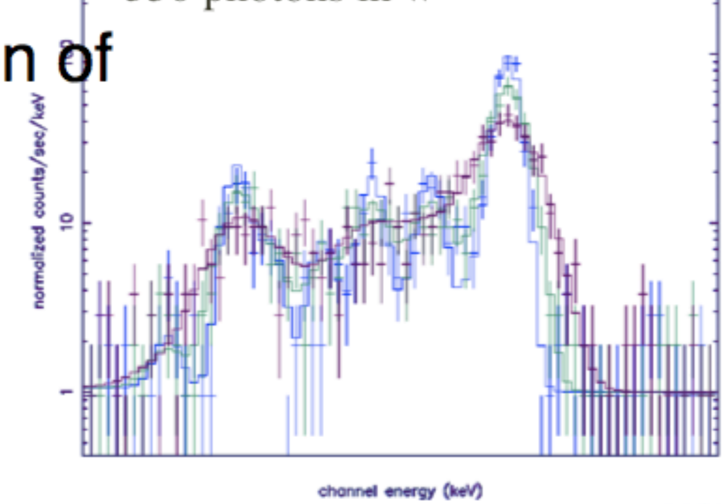
Astro-E2 XRS simulation




Inogamov and Sunyaev 2003

Turbulence & Thermal motion of Fe ion

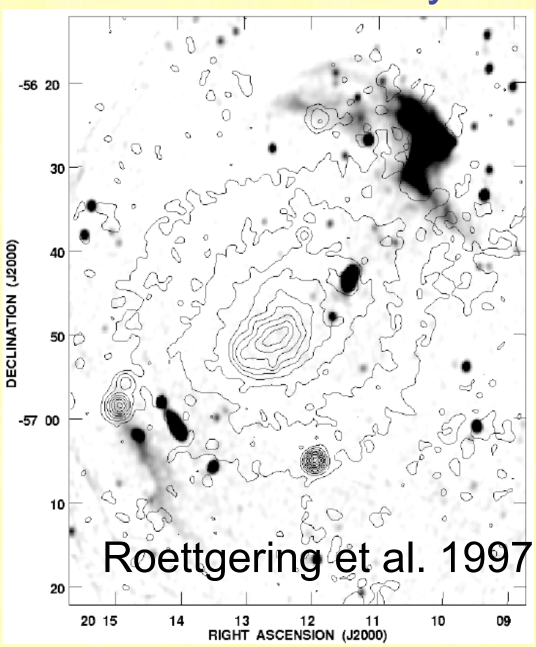


# Strategy of NEXT

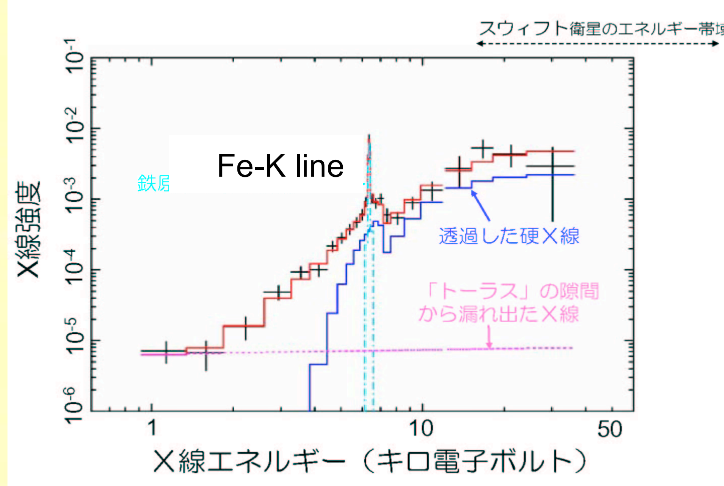
Combination of gas dynamics (SXS), hard X-ray image (HXT) and 300 keV spectrum (SGD):

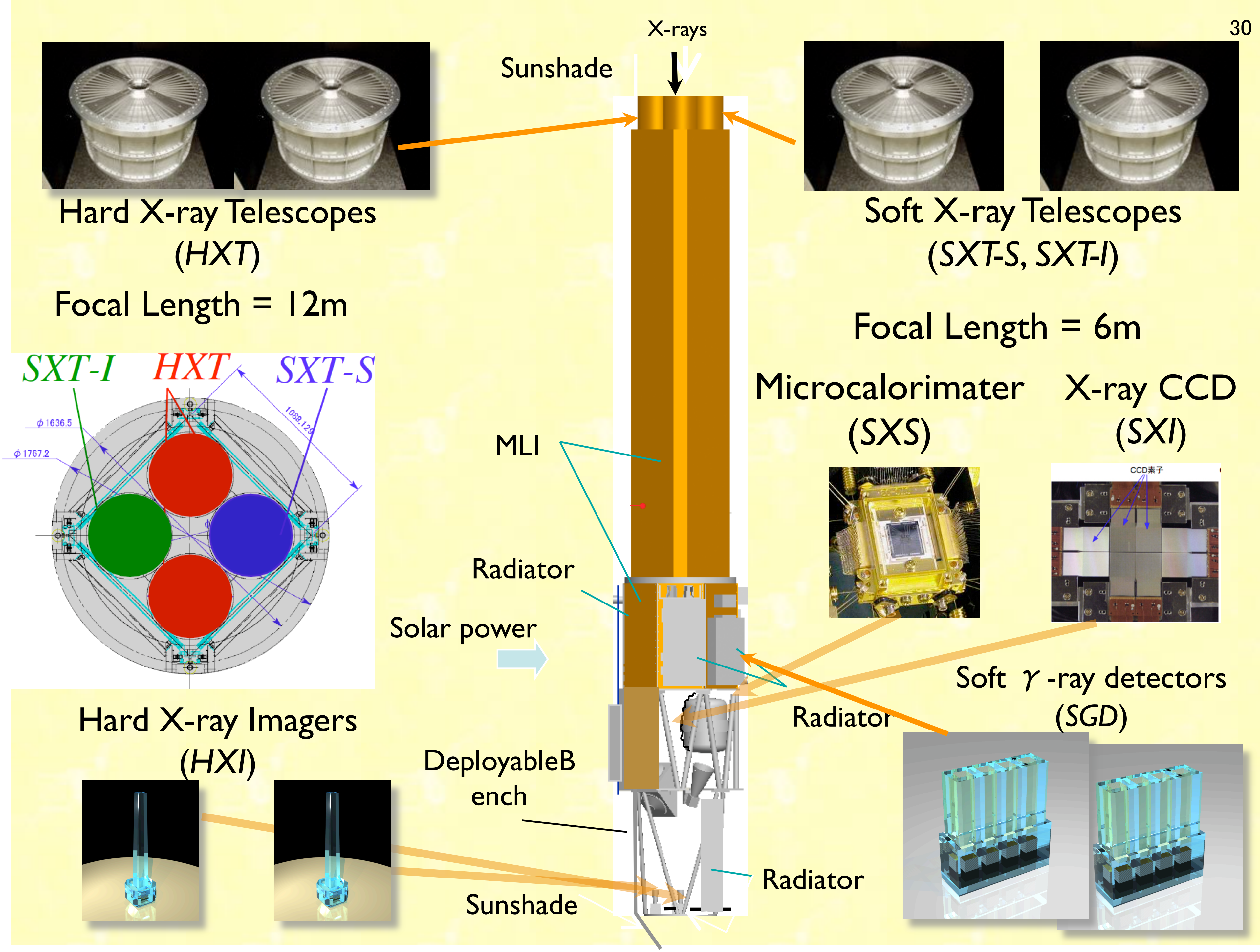
- Complete picture of non-thermal process in galaxies and clusters: galactic winds and cluster mergers
- Obscured AGNs: hard-X and Fe-line to probe surrounding medium

A3667: Radio & X-ray




Swift J0601.9-8636: Ueda et al 07

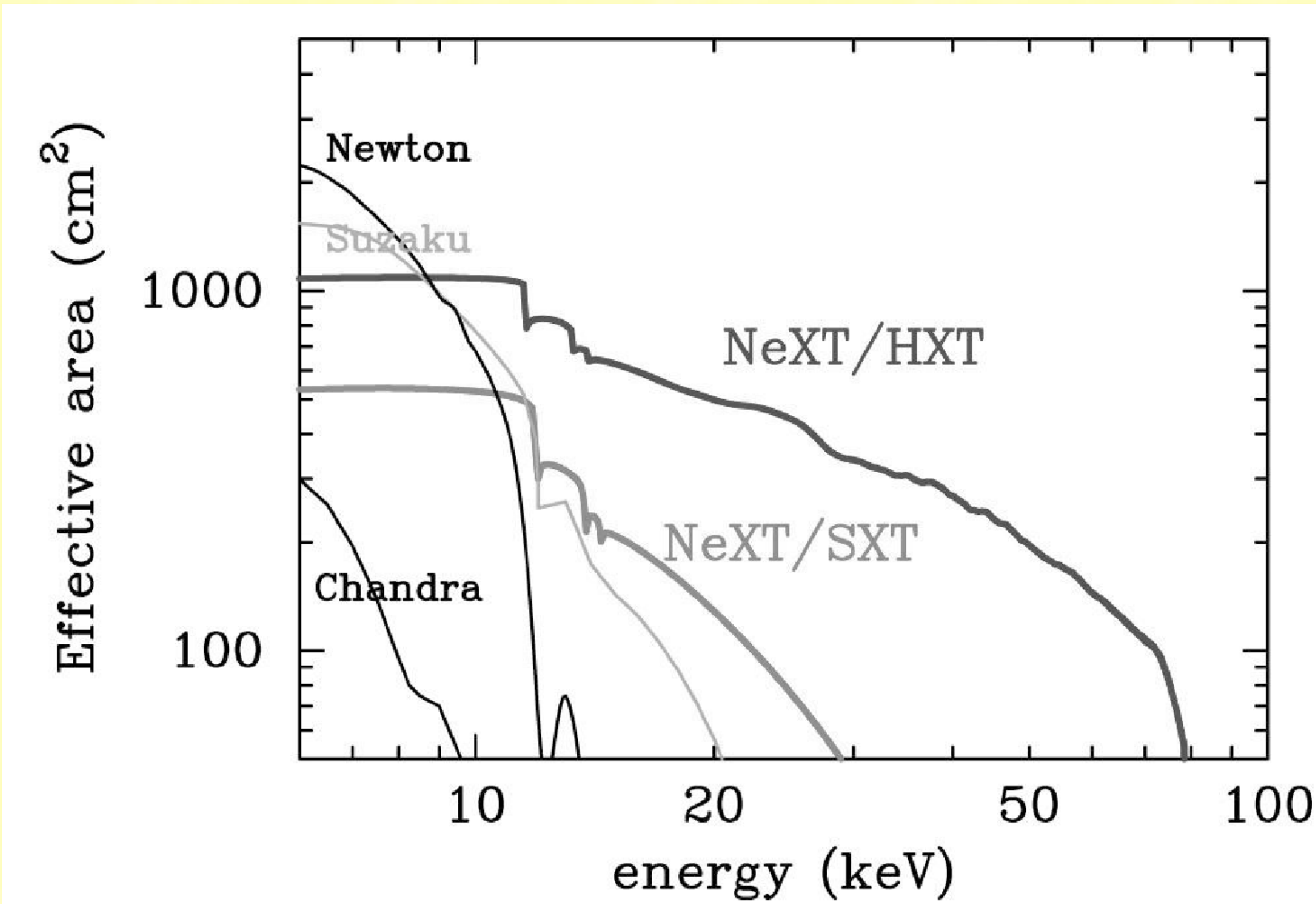



X-rays
Sunshade
Hard X-ray Telescopes
(HXT)
Focal Length = 12m
Soft X-ray Telescopes
(SXT-S, SXT-I)
Focal Length = 6m
SXT-I
HXT
SXT-S
MLI
Microcalorimater
(SXS)
X-ray CCD
(SXI)
CCD素子
Radiator
Solar power
Soft γ-ray detectors
(SGD)
Radiator
Hard X-ray Imagers
(HXI)
DeployableB
ench
Radiator
Sunshade

# NeXT Performance

| | Requirement |
|---|---|
| Hard X-ray Imaging System (HXT+HXI) **5-80 keV** | Angular resolution 60” Effective Area 340cm$^2$ @30 keV Energy resolution 2 keV |
| Soft X-ray spectroscopy System (SXT-S+SXS) **0.3-10 keV** | Energy resolution 5-10 eV In-orbit life 3 years Sensor size 25 mm$^2$ |
| Soft X-ray Imaging System (SXT-I+SXI) **Requirement: 0.5-12 keV** **Goal: 0.3-25 keV** | Angular resolution 60” Effective area 530cm$^2$@6 keV Energy resolution 150 eV Imaging area size 5cmx5cm |
| Soft Gamma-ray Detector (SGD) **10-300 keV** | Detector background $1 \times 10^{-5}$ ph cm$^{-2}$ s$^{-1}$ keV$^{-1}$ |

# Telescope effective area




International collaborations of NeXT
• Science Payloads
– HXT: J, US
– SXT: J, US
– HXI: J, US
– SXI: J, US
– SXS: J, US, ND
– SGD: J, US
• Science working group and Joint Data Center (to be organized in this year)
– US, Europe, and other countries
• Joint System Engineering Team and Technology working group (to be organized in this year)
– especially with US

# Final summary

- Missing baryons (and accompanying missing dark matter) are important and only probed with X-ray observations
- Microcalorimeters (small $\Delta E$, wide area, angular coverage) can achieve various unique science (missing baryons, dynamics, chemistry…)
- Hopefully, NEXT (& SRG) will give a new momentum to X-ray astronomy